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RESEARCH PAPER

Allometric equations for estimating leaf area index (LAI) of two important tropical species (*Tectona grandis* and *Dendrocalamus strictus*)

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Abstract: Leaf area index (LAI) of Teak (*Tectona grandis*) and Bamboo (*Dendrocalamus strictus*) grown in Shoolpaneshwar Wildlife Sanctuary of Narmada District, Gujarat, India was obtained by destructive sampling, photo-grid method and by litter trap method. An allometric equation (between leaf area by litter trap method and canopy spread area) was developed for the determination of LAI. Results show that LAI value calculated by the developed allometric equation was similar to that estimated by destructive sampling and photo-grid method, with Root Mean Square Error (RMSE) of 0.90 and 1.15 for Teak, and 0.38 and 0.46 for Bamboo, respectively. There was a perfect match in both the LAI values (estimated and calculated), indicating the accuracy of the developed equations for both the species. In conclusion, canopy spread is a better and sensitive parameter to estimate leaf area of trees. The developed equations can be used for estimating LAI of Teak and Bamboo in tropics.

Keywords: bamboo; canopy spread area; leaf area index; specific leaf area; teak; tropical forest

Introduction

Leaf area index (LAI) is an important parameter in the functioning of forests controlling plant productivity and exchange of energy between vegetation and atmosphere (Moser et al. 2007). It provides apt information for the evaluation of primary production of forest ecosystem. LAI is defined as the cumulative one sided surface area of the leaves in the canopy per unit ground area. Finding out a suitable allometric relationship between leaf area and other biophysical parameters of trees (diameter at breast height (DBH), tree height, and litter mass) is also an important aspect of tree research. However, LAI is one of the most difficult parameters to quantify properly, owing to large spatial and temporal variability (Breda 2003). Many studies were carried out for LAI of temperate forests (Sellin 2000; Temesgen and Weiskittel 2006; Weiskittel and Maguire 2006; Urban et al. 2008). A few studies on the LAI have also been conducted for tropical ecosystems (Maass et al. 1995; Nascimento et al. 2007). LAI can be determined by harvesting, litter trap or by optical methods. The common indirect optical methods are radiation measurement based on Beer-Lambert law, using canopy analysers (Li-Cor, Delta T devices), hemispherical photography, and remote sensing (Blackburn and Steele 1999; Dovey and Toit 2006; Nascimento et al. 2007; Urban et al. 2008). However, all the indirect methods have their own limitations. For instance, optical sensors fail to function perfectly in dense, multi-layered canopy system commonly in tropics (Moser et al. 2007).

Direct methods for leaf area (LA) estimation are expensive and time consuming, and easily lead to the destruction of the sample. It is equally impossible to execute for large tracts of vegetal cover. Therefore, indirect methods have been used to determine LAI with low accuracy for some important tropical forest trees (Maass et al. 1995; Dovey and Toit 2006). The cross-validations between direct and indirect methods have pointed to a significant underestimation of LAI with indirect methods (Breda 2003). Mass-based (direct) approaches are comparatively more accurate than optical (indirect) approaches for LAI measurements across environmental gradients (Khan et al. 2005). Plant ecologists are interested to determine LAI preferably by indirect method (even with lesser accuracy) in order to prevent destruction of the sample. An easy and accurate method is needed to estimate the LAI of vegetation, especially tropical forests. Tropical deciduous trees are unique in having complete leaf shedding in short span of time. In deciduous stands, a non-destructive method consists of collecting leaves in traps distributed below the canopy during leaf fall (Breda 2003). Khan et al. (2005) found a relationship between leaf area, above ground biomass and DBH of mangrove trees. Allometric equations relating to litter mass and DBH can be used to estimate LAI by having specific leaf area (SLA) (Gower et al. 1999). Many studies have shown a relationship between foliage mass and other biophysical parameters such as litter dry matter content, tree diameter and crown surface

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area (Makela and Albrektson 1992; Li et al. 2005; Pretzsch and Mette 2008). For the determination of LAI, exact and accurate estimation of total LA of a tree is essential. The current study was carried out to estimate LAI by developing an allometric relationship between LA and spread of canopy for two important tropical deciduous species, *Tectona grandis* (L.) and *Dendrocalamus strictus* (Nees.).

Materials and methods

Study area

The study was conducted at Shoolpaneshwar Wildlife Sanctuary (SWS) of Narmada District, Gujarat, India (21°29'N–21°52'N and 73°29'E–73°54'). SWS occupies an area of 675 km^2. Annual rainfall of the area is in the range of 900–1200 mm. Rainfall starts from the last week of June and is restricted to the months of June–October. Minimum (8°C) and maximum (42°C) temperatures are recorded in winter and summer, respectively. Vegetation cover of the SWS is mostly deciduous in nature. Teak (*Tectona grandis* L.) and Bamboo (*Dendrocalamus strictus* Nees.) are the most dominant species of the study area. Other species also growing in the sanctuary are *Butea monosperma* (Lamk.), *Holarrhena antidysenterica* (R.) Br, *Mitragyna parviflora* (Korth.), *Dalbergia latifolia* (Roxb.), *Anogeissus latifolia* (Wall.), *Bridelia retusa* (L.), *Albizia lebbeck* (L.), *Madhuca indica* (Gmel.), *Garuga pinnata* (Roxb.), *Pongamia pinnata* (L.) and *Ficus racemosa* (L.). Density of vegetation in the sanctuary is approximately 650 individuals·ha^{-1} Teak trees, 350 individuals· ha^{-1} Bamboo clumps, and 650 individuals·ha^{-1} of mixed trees. Soils are reddish-brown in colour and loamy. Alluvium deposits of clay-loam type are also seen with light brown to grey black colour (Gujarat state Forest Department, unpublished data). Two important species (*Tectona grandis* L. and *Dendrocalamus strictus* Nees.) were chosen to develop an allometric equation between leaf area and canopy spread. A few patches of Teak and Bamboo growing in neighbouring district, Vadodara were also identified to test the validity of the developed allometric equation.

Measurement of Biophysical parameters

Biophysical parameters such as height of the tree, diameter at breast height (DBH) and canopy spread were measured for both the species. About 15 individuals of each species were picked up from a 30 × 30 m plot for measurements. Measurements were carried out at ten plots. Height of the tree was measured by using Ravi's multimeter (indigenous equipment). The instrument works on trigonometric principle. DBH and canopy spread were measured using a metre tape. For each tree, canopy spread was measured in four opposite directions. Subsequently mean canopy spread of each tree was calculated. These values were considered as radius for each tree's canopy area. By using πr^2 canopy spread area of each tree was calculated.

LAI from litter trap method

Litter was collected from the forest floor of Teak and Bamboo at quarterly intervals for one year. More than 95% of litter collected comprised of leaves. Litter fall was the maximum in summer. Litter was collected from randomly laid quadrats of 1 m^2 size on the marked forest floor. We assumed that most of the leaves (>90%) of a tree will fall within its canopy spread area during litter fall. Any exchange would be uniformly compensated. At each point 5–8 quadrats were laid. From the collected litter, pieces of branches (if any) were removed (<5% by weight). The rest (>95%) was of leaves. This was transferred into plastic bags, oven dried for 48 h at 70°C, and dry weights were measured. Extreme values were discarded while pooling the data. Readings of peak litter fall period (summer) were used. Average litter fall values (m^{-2}) were obtained from five readings of each plot. Values coming from 10 plots for each species were pooled again to obtain mean litter weights of unit canopy spread area (m^{-2}). From these pooled average values (of Teak and Bamboo), total weight of the leaves fallen under canopy spread area of each individual tree was calculated. This was considered as foliage biomass of the tree. Independently 15–20 mature leaves of both the species were plucked from five trees with different canopy spread areas. Leaf area and dry weight of these leaves were measured. Subsequently mean specific leaf area (leaf area/ dry weight) for both the species was calculated. Leaf area of each tree was calculated by multiplying obtained foliage biomass of the tree with specific leaf area. LAI was estimating by dividing leaf area of a tree with canopy spread area.

Allometric equation

A simple linear regression equation was developed by taking canopy spread area and estimated leaf area of a tree as variables. Trees with different canopy spread areas were identified. Corresponding leaf area was calculated. Both these values were regressed.

Validation of regression model by destructive sampling and photo-grid method

LAI of the Teak and Bamboo trees growing in Vadodara district was measured by destructive sampling and also by photo-grid method. Twenty trees (12 for Teak, 8 for Bamboo) having similar DBH were considered. Canopy spread and subsequently canopy spread area were measured. Canopy of the Teak was vertically stratified into segments (3-6 depending on canopy height) from the base of canopy up to its tip. From each segment, 20%–25% of leaves were plucked and their leaf area was measured by using graph paper. Leaf area values of each segment were obtained by extrapolating actual readings of 20%–25% of foliage. The leaf area values of all the segments of a tree were summed up to obtain leaf area of the Teak tree. These values were used to calculate LAI of 12 Teak trees. In Bamboo, the number of stumps in each clump (Bunch of individual stem/stump of bamboo) was counted, and 5–6 representative stumps were identified. Leaf samples of these stumps were collected and leaf area was estimated by using graph paper. Average leaf area of a stump was calculated. Subsequently leaf area of each clump was obtained (leaf area of stump × number of stumps in a clump). These values were used to calculate LAI of 8 individuals of Bamboo.

Another 20 trees of similar description were taken for photo-grid method. Each tree was photographed in 4–6 directions. A ruler was included in the canopy while clicking. Number of snaps was proportional to height of the tree. Pictures taken were observed in Adobe Photoshop. Each picture was superimposed on a

1×1 grid. Each grid was considered as a pixel. Actual number of leaves in 5−10 pixels was counted. Mean leaf number of a pixel was obtained. Total number of pixels in photographs of each tree was obtained. Care was taken to avoid repetition of the same area in calculating pixels. Total number of leaves of a tree was obtained (number of pixels× mean number of leaves in a pixel). This number was multiplied with mean leaf area (coming from 20 mature leaves) to obtain leaf area of the tree. Total leaf area of 20 trees was used to calculate LAI of each tree. Canopy spread area of these 40 trees (24 for Teak and 16 for Bamboo) was taken to estimate leaf area of each the tree species by using the allometric equations developed. LAI of these 40 trees was obtained on the basis of the leaf area values. LAI values of 40 trees (coming from destructive sampling, photo-grid method and from allometric equation) were evaluated against each other with the help of Root Mean Square Error (RMSE). RMSE was used to measure the average difference between predicted and observed parameters. RMSE between predicted and observed parameters was calculated by the equation 1.

$$\mathrm{RMSE}=\sqrt{\frac{\sum (P_i-O_i)^2}{n}} \qquad (1)$$

where P_i the predicted value, O_i is the observed value. Here, predicted values are obtained from the developed equation while the observed values are from the destructive sampling and photo-grid method.

Results

Litter production increased from September to the peak at the next June. In June the canopy was completely leafless. Dry weight of fallen litter was higher in Teak compared to Bamboo. Dispersion of the values of fallen litter at most of the points is relatively less. Amount of fallen litter was proportional to canopy spread area in both the species. SLA values were more in Bamboo compared to Teak. Biophysical parameters of Teak and Bamboo trees were mentioned in Table 1. Leaf area values of individuals calculated by weights of foliage biomass and SLA values were high and increased with the increase in the size of individual/canopy spread area. Allometric equations were developed between these leaf area values and respective canopy spread area (Fig. 1). Leaf area values of another set of individuals, estimated by destructive sampling and photo-grid method were given in Fig. 2. Here also leaf area increased with an increase in the size of individual. The values of leaf area obtained by both the methods are almost similar for individuals with the same size. Correlation coefficient between leaf area values coming from both the methods was very high (Fig. 2). For all these individuals leaf area was calculated using the allometric equation developed. The calculated values were very close to the values estimated by the direct method (Fig. 3). Similar estimates developed between leaf area and DBH did not give better correlation (Fig. 4). Leaf area values obtained from different trees were used to calculate LAI. LAI values of Teak and Bamboo were 6.56 and 5.08, respectively. LAI values coming from the developed allometric equation and destructive sampling are matching with each other (RMSE 0.90 for Teak; 0.46 for Bamboo). Similar, results were also found among LAI values coming from the developed allometric equation and photo-grid method (RMSE 1.15 for Teak and 0.38 for Bamboo).

Table 1. Biophysical parameters of Teak and Bamboo trees of ten different study plots (n= 150 for both the species)

No	Teak DBH (m)	Teak Canopy Spread (m)	Teak Canopy Spread Area (m^2)	Bamboo DBH (m)	Bamboo Canopy Spread (m)	Bamboo Canopy Spread Area (m^2)
1	0.25±0.01	3.53±0.21	39.02±4.71	1.72±0.26	4.80±0.40	72.35±12.15
2	0.18±0.03	2.40±0.42	18.09±6.24	1.11±0.08	2.93±0.39	26.86±7.12
3	0.21±0.03	2.00±0.20	12.56±2.52	0.80±0.12	3.10±0.64	30.18±12.19
4	0.13±0.02	1.70±0.17	9.07±1.80	1.75±0.14	3.45±0.39	37.37±8.48
5	0.22±0.02	2.93±0.15	26.86±2.84	1.66±0.19	3.35±0.77	35.24±15.77
6	0.17±0.03	2.15±0.29	14.51±3.86	1.11±0.09	3.53±0.40	39.02±8.79
7	0.21±0.04	3.10±0.27	30.18±5.15	1.11±0.09	3.35±0.61	35.24±12.56
8	0.16±0.03	2.30±0.41	16.61±5.85	1.91±0.08	4.95±0.37	76.94±11.45
9	0.19±0.03	2.80±0.44	24.62±7.57	1.78±0.08	4.60±0.50	66.44±14.21
10	0.26±0.03	4.23±0.11	56.05±2.95	2.07±0.06	3.43±0.51	36.83±10.94

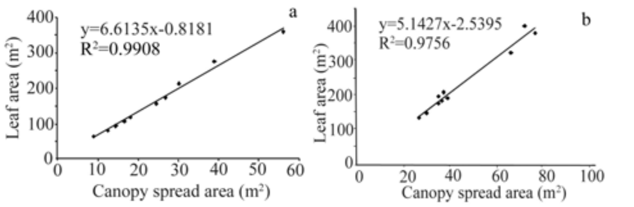

Fig. 1 Allometric relationship of LA to Canopy spread area of Teak (a) and Bamboo (b)

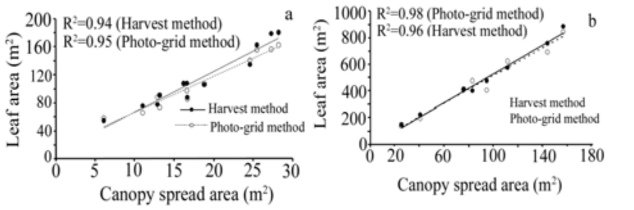

Fig. 2 Correlation of leaf area derived from photo-grid and harvest methods of Teak (a) and Bamboo (b) with canopy spread area.

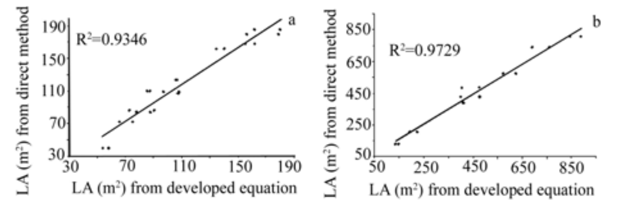

Fig. 3 Correlation between the leaf area of Teak (a) and Bamboo (b) derived from the developed equation and the destructive sampling and photo-grid method.

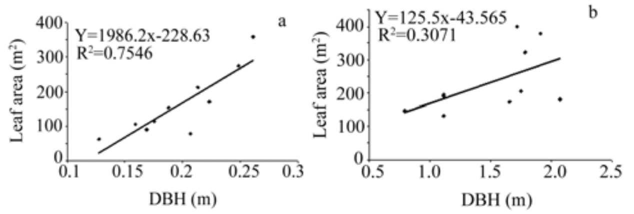

Fig. 4 Allometric relationship of leaf area to diameter at breast height of Teak (a) and Bamboo (b).

Discussion

Results of our study indicate a perfect correlation between leaf area and canopy spread area. Estimation of leaf area index from the developed allometric equation gave values similar to the ones coming from direct methods of estimation. This confirms the better functioning of the developed equations for estimation of LAI of Teak and Bamboo. LAI has a close correlation with many bio-physical changes of a tree; therefore, estimation of LAI is an important aspect for understanding the functioning of tropical trees. Most of the published results come from temperate regions (Sellin 2000; Temesgen and Weiskittel 2006; Weiskittel and Maguire 2006; Urban et al. 2009) and there are only a few reports for tropics (Maass et al. 1995; Moser et al. 2007). It is very important to have standardized equations for the estimation of LAI for tropical trees. Results of this study make an attempt to fill this void. At least for two important species selected the allometric equation worked with high accuracy. Earlier reports (Mussche et al. 2001; Breda, 2003; Asner et al. 2003) concluded that indirect methods underestimated LAI as compared to direct methods. Results of this study indicate that the developed indirect method is equally better with two of the most commonly used direct methods (destructive and photo-grid). There is no under- or over- estimation. Results of SLA showed difference in the leaf morphology of both the species. They differed with variations in the thickness of leaves as reported earlier (Witkowski and Lamont 1991; Wilson et al. 1999). Litter production was the maximum in both the sites at the end of summer, indicating the severity of the season as well as the deciduous nature of trees. Pande (2005) reported that annual litter production of Teak ranged from 3.27–4.53 $Mg \cdot ha^{-1} \cdot a^{-1}$. In the present study, the litter fall values of Teak were relatively higher (3.28−5.99 $Mg \cdot ha^{-1} \cdot a^{-1}$). This unique leaf fallen pattern helped us in calculating leaf area with better precision by litter trap method. Breda (2003) envisaged the importance of fallen litter values in estimating LA for deciduous trees. Results of our study support the view. Our estimates of mean LAI for the two tropical species are similar to the values reported earlier (Maass et al. 1995; Yang et al. 2006; Moser et al. 2007; Ganguly et al. 2008). Moreover, the values are in a narrow range irrespective of coming from direct methods or from the allometric equations.

Estimates developed between LA and DBH of trees did not give better correlation (Khan et al. 2005; Gower et al. 1999). We tried to test the correlation between LA and DBH. The correlation coefficient values are much lower (Fig. 4) compared to the ones coming from LA and canopy spread area (Fig. 1). It implies that canopy spread area is relatively more sensitive to LA as compared to DBH. Any small variations are noticeable as canopy spread area is much larger for a tree than its DBH. The relationship between LA and canopy spread area worked well for Teak and Bamboo in this study. Usage of canopy analyser has a major limitation when the tree cover is dense, and has lianas or thick ground cover. The allometric relation developed here will not be affected by any of these factors thereby giving a better estimate for LA of a tree. The study can be extended to other tropical trees for LAI estimation.

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